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INTERIM REPORT ON CAPABILITIES OF THE EXPERIMENTAL LARGE APERTURE SEISMIC ARRAY

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ABSTRACT

This report presents an interim appraisal of capabilities of a single Large Aperture Seismic Array system to perform the following functions: (i) preprocess arriving seismic signals to increase their detectability, (ii) use such preprocessed signals to perform on-line automatic detection and location, (iii) process recordings of LASA data off-line, and (iv) use the results of the off-line processing for studies of seismic source type.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

INTRODUCTION

This report presents an interim evaluation of performance of the experimental Large Aperture Seismic Array in Montana. This array is part of the national Vela Uniform program intended to advance the seismology art in general and in particular to provide increased capability to distinguish between underground blasts and earthquakes.

Briefly, the mode of operation of the LASA is as follows. A total of 525 short-period vertical seismometers are distributed over a roughly circular region 200 km in diameter in eastern Montana. The separate outputs of these seismometers are transmitted to a LASA Data Center in Billings, Montana. In the LDC there are several digital computers with associated recording and display equipment. The 525 seismometer outputs are continuously recorded on digital magnetic tapes with provisions for saving a given LASA tape if automatic event detection and source location computer programs designate the recorded time period as containing an event of interest. Otherwise the tape is erased and reused. If a tape is saved, it can then be processed off-line to bring out the pertinent signal features.

This off-line processing is referred to as post-detection processing. To insure that the event detection and location functions, which cause a LASA tape to be saved in the first place, will function on sufficiently small seismic magnitudes, some array data processing to increase the signal-to-noise ratio (SNR) must be done in real time at the LDC. This is called predetection processing, and must occur on-line and on-site. In

post-detection processing, signal distortion must be carefully controlled since it might obscure important signal features. In predetection processing on the other hand, one needs only an indication of signal presence or absence plus time of occurrence to permit making a decision between retaining or erasing a tape of unprocessed data. Thus with predetection processing one is free to extract larger SNR gains by allowing signal distortion.

The initial complement of on-site signal processing equipment includes two general-purpose digital computers and one small special-purpose machine, the Texas Instruments digital MCF (Multichannel Filter). At the present time, all portions of the Montana LASA are operating with the exception of the second general-purpose computer, which has yet to be delivered.

In this report we present an appraisal of capabilities of the experimental LASA as inferred from results up to 1 February 1966. The problem divides naturally into four areas: (i) capability to decrease the minimum detectable seismic magnitude by predetection processing, (ii) capability for automatic event detection and location, (iii) increase of SNR by post-detection processing, and (iv) the improvement of seismic source discrimination afforded by this post-detection processing. In the next four sections of the report, these areas are discussed in order. We now have reasonably complete results on item (iii), while results on item (iv) are least complete.

I. LASA DETECTABILITY THRESHOLD

One is interested in depressing the seismic magnitude of the minimum detectable signal to as low a figure as possible. This is desired for monitoring underground nuclear tests of small yield and for conducting certain seismological research (for example, the rapid accumulation of a large sample of similar events or the study of small strain releases). It is not considered sufficient that the LASA detect, locate, and record only those events large enough to be seen on unprocessed single traces, even though a large part of the future use of the system is certain to involve such large events. For example, an event that is easily detectable on a single trace may still require a large SNR improvement for discrimination of source type.

After effective predetection processing is implemented at Billings and a large sample has been built up of several hundred small events which are barely detectable after the processing, it will be possible to give a definitive figure on the LASA detection threshold magnitude. At present it must be inferred indirectly. This is done by first attempting to find the seismic magnitude for single-sensor detectability and then subtracting from this the difference in magnitude equivalent to the SNR gains of the expected forms of predetection combining of multiple traces.

The magnitude above which 50% of the total events in the 50 to 85 degree range of epicentral distance are detectable by eye on raw traces appears to be 4.1. This figure was arrived at as follows. Figure 1 shows a plot of number of events larger than a given magnitude detected during a one-month period as a function of that magnitude.

The circles represent those reported by the U. S. C. & G. S. The triangles are for those seen by monitoring just two particular LASA seismometers. We make the hypothesis that the natural law of seismicity is such that the straight line one gets when all events are seen (m > 4.8) extrapolates below 4.8. If this is true, the magnitude threshold for detecting 50% of all events on a LASA sensor is 4.07 (that for U. S. C. & G. S. is 3.95). When enough events have accumulated from a specific region or two the study will be repeated for these regions.

Data has been obtained on predetection processing gain by two means, (i) off-line processing on the Lincoln Laboratory 7094 of LASA tape recordings, using simulations of some of the processing schemes that it is feasible to implement on-line, and (ii) actual use of on-line equipment at Billings, specifically the PDP-7 and MCF (multichannel filter). In both instances processing schemes studied have included fairly sophisticated ways of combining a few traces (say 25) and also simple ways of combining many traces (up to the total 525).

To increase the signal-to-noise ratio, both frequency filtering and spatial filtering are employed. The P-wave frequency spectrum appears to vary somewhat from event to event. Although some initial experiments were performed by prefiltering all traces with identical filters only 0.1 or 0.2 cps in their 3 db bandwidth, it was necessary to standardize on a wider prefilter having a flat top and a 3 db passband of 0.6 to 2.0 cps, so as to avoid missing some events.

Spatial filtering, i.e., array processing, of traces that have been subjected to bandpass prefiltering can be done by several means. Figure 2 shows the results of off-line array processing of various numbers of prefiltered LASA traces using various methods. Combinations of three increasingly more effective but more complex forms of processing have been investigated. The heavy lines in the figure show the SNR gain achieved using Filter-and-Sum processing (FS), which is the most general form of linear signal combining scheme. In this method, a filter is applied to each sensor output before summing. This filtering operation, which is a different operation for each sensor should not be confused with the prefiltering of all traces by the same filter, as just discussed. We used a particular form of FS called "adaptive maximum-likelihood" processing in which the N filters that were set up in the computer were designed to pass the signal from a known direction undistorted while minimizing output noise having the statistical character of the noise observed in the three-minute interval preceding the event. This observation interval is called the fitting interval. The thin lines in the figure denote simple Delay-and-Sum processing scheme (DS), in which each sensor output is subjected to only an appropriate steering delay before summation. Weighted Delay-and-Sum (WDS) processing, indicated by dashed lines, is a scheme of intermediate complexity in which, in addition to a steering delay, each sensor output is multiplied by an amplitude weight. The set of amplitude weights was designed to minimize noise of the type observed in a three minute fitting interval.

In Fig. 2 the ordinate is the ratio of output SNR to the average of the SNRs of the N inputs. Vertical lines show SNR gains obtained by applying one of the three standard

schemes to N sensors. For some of the $N > 25$ points (more than one subarray) the traces were combined in two steps. For example, the upper number on the far right (22 db) was obtained by DS processing of each of 19 sets of 25 sensors followed by a DS combination of the 19. This is indicated by a vertical thin line at $N = 25$ leading to a slanting thin line extending to $N = 19 \times 25 = 475$.

As discussed in the next section, bandpass prefiltering of a single trace results in a P-wave detectability by machine that is comparable to, or slightly better than, that of the eye looking at the same unfiltered trace. Since Figure 1 is based on visual detection operations, the ordinate values given in Fig. 2 represent the amount by which one expects the detection threshold of Fig. 1 to be lowered by combining N prefiltered traces into one trace in the stated manner and feeding this trace to the event detector instead of a raw trace. Each 1.0 difference in seismic magnitude is equivalent to 20 db.

It is observed that the ordinate values range as high as 22 db (1.1 mag) for the methods tried. Considerable computing complexity is needed to achieve this, however. Beside each point in Fig. 2 are two numbers, the bottom one indicating the number of runs averaged to get the plotted value and the top one indicating the number of minutes of 7094 time needed to do the complete processing job for that form of processing, including measurement of noise statistics from the three-minute sample, design of an optimum filter or weight for each trace and then actual application of the processing to the traces. It is seen from the upper numbers that in some cases large amounts of computation were required. This can be mitigated to some extent by remeasuring noise

statistics infrequently, by using special-purpose equipment, and by other means that are discussed in more detail in Section III in connection with post-detection processing. Thus, these numbers should not be taken as literal indications of the time and equipment that will be necessary on-site to get a given SNR gain, but rather as an indication of relative complexity. Numbers in parentheses represent computed rather than observed 7094 computing time.

The MCF unit presently at Billings does predetection processing by FS combining of 25 sensors with up to 78 sample points per filter, and in fact can produce five differently derived such FS outputs on the same 25 sensors. This represents a complex way of combining a few traces, namely 25, and results in a fairly broad surveillance beam if the 25 sensors used come from the same subarray. We are also employing the converse, a simple method of combining many traces by a form of DS processing of all the sensors, using the PDP-7 computer. To do this, straight sums are formed by analog means at each subarray and when these signals reach the PDP-7 they are subjected to DS operations to form five different directive beam outputs. These beams are quite narrow (Fig. 3).

The SNR gains plotted in Fig. 2 are those observed 30 seconds after the end of the three-minute fitting interval. We have observed that sizable losses of SNR can occur outside the fitting interval. Within this interval the SNR gains are 2 db higher than those shown in the figure for all FS data and 0.5 db higher for WDS. Several minutes after the end of the fitting interval the SNR gains are about 2 db lower than the

values shown for FS and 0.5 db lower for WDS. The loss after that time fluctuates with the nonstationary character of the cultural noise. It appears to be no more than about 6 db for FS and 2 db for WDS on the average after an interval of several hours to a week.

From Point A in Fig. 2 one concludes that by updating the processor parameters promptly (within several tens of seconds) 12 db (0.6 mag) of predetection SNR gain (i.e., 0.5 to 2.0 cps) is achievable on a single subarray using FS. This can be implemented in the on-site MCF unit. A more realistic figure based on updating after minutes would be $12 - 2 = 10$ db (0.5 mag). The beamwidth for a single subarray is probably large enough so that five differently-aimed outputs from the same MCF unit (such as are available from the one now at Billings) ought to suffice for monitoring all regions of interest. $20 - 2 = 18$ db (0.9 mag) would be available (Point B) from DS combining of five subarrays (in a PDP-7, for example) which would require five MCF equipments updated every few minutes, and would result in a narrow main beam something like that shown in the legend of Fig. 3, if the five subarrays used were A0 and the four F-ring subarrays. A similar main lobe with a $23 - 2 = 21$ db SNR gain (1.05 mag) should be obtainable from FS combining of 21 individual subarray DS outputs (extrapolation of Point C from 19 to 21 subarrays); this could be done by a PDP-7 preprocessing operation to do DS on 21 subarrays, the outputs then being fed into a 21 input MCF unit. Other combinations will readily come to mind, and the effectiveness of many of them can be gauged from Fig. 2.

In the present on-line operations of the MCF and the PDP-7 beamformer program we are obtaining further experimental results. The average SNR gain of the PDP-7 beams for three events examined so far is 13 db, as indicated by Point D in Fig. 2. More data on this is being accumulated, and similar experiments are in progress using the MCF equipment. The on-line beams are formed using theoretical (J-B) travel times from a hypothetical epicenter, modified by an estimate of the station corrections. These estimates, which are now fairly reliable, are updated as our knowledge of the station corrections improves. That the present steering is reasonably accurate can be seen from the beam waveform quality for events with simple waveforms. We hope that as the station corrections improve, Point D in Fig. 2 will move upward toward the off-line DS data which were obtained by careful eyeball alignment of all traces before combining of separate subarrays.

We can summarize the data presented in this section as follows:

(1) From very limited data the raw trace 50% threshold magnitude appears to be 4.1 over a 50^{o} to 85^{o} distance range. The 75% threshold is 4.3.

(2) On-site SNR improvements averaging 0.65 mag have been observed using a simple program that forms a narrow beam (Point D in Fig. 2).

(3) A direct determination of the new detection threshold after either beamforming or MCF subarray processing on-site has not been made. The first of these is appropriate to surveillance of a previously designated region of the earth and the second to surveillance of very large regions.

(4) Off-line processing results indicate that a lowering of the single-sensor threshold by the following amounts should be possible using the presently unrealistic procedure of keeping the processing completely updated (to within several minutes of the event).

(i) 0.5 mag with a wide beamwidth using one MCF unit (Point A)

(ii) 0.9 mag with a narrow (Fig. 2) beamwidth using 5 MCF units plus a simple beamforming program (Point B)

(iii) 1.0 mag with narrow beamwidth using simple (DS) beamforming with each of the 21 subarrays followed by processing in one MCF unit.

Current work on methods of on-line updating could eventually make these figures achievable.

(5) Off-line processing results indicate that if the processors are updated only once every several days, these three figures now become

(i) 0.3 mag

(ii) 0.7 mag

(iii) 0.8 mag .

II. AUTOMATIC EVENT DETECTION AND LOCATION

We mentioned in the last section two approaches that are being taken to the problem of lowering the detection threshold by predetection processing. These are on the one hand the use of broad-beam complex processing (FS) of a few of the LASA sensors as is done in the MCF equipment, and on the other hand narrow-beam simple processing (DS) using all 525 sensors as is done in the PDP-7 beamformer program.

These two processing approaches are the basis of two corresponding approaches to the automatic event screening problem. In the first of these, predetection processing is done on only a few widely spaced subarrays, an event detector is applied to each output, and a "majority vote" decision on the event detector output signals from these event detectors determines whether or not a teleseism was received. Time of arrival determinations from the event detectors provide the data for event location by triangulation. In the second approach, using the PDP-7 beamformer outputs, an event detector is applied to each beam. An output from any detector implies an event somewhere, and the location is found by determining which beam contains the strongest signal or by interpolating between beams.

We are pursuing in parallel these two approaches to event detection and screening. When we understand them more thoroughly it will be possible to select one or the other (or perhaps the simultaneous use of both) for the operational LASA design. This decision will depend on the actual uses to which a LASA is to be put; for example, whether full predetection sensitivity is required with very wide geographical coverage, or whether some or all of the regions of interest can be specified beforehand.

We define an event detector as a device or sub-program designed to accept a single trace as its input and to provide an output signal at (and only at) the beginning of a P-wave arrival. Our basic event detector, which operates on a single trace, produces a trigger by determining when the energy in a narrow filter tuned to the P-wave frequency undergoes a sudden increase. Specifically, the signal from one trace is passed through a narrow filter (0.95 cps to 1.45 cps in previous tests), rectified and compared to a reference level. The reference level is obtained by integrating this same rectified output for 30 seconds and then delaying by five seconds. If the rectified output exceeds the reference level by some preset amount, a trigger is produced.

This logic is replicated a number of times in the PDP-7 machine so that a number of traces can be monitored simultaneously. In most of our work so far the event detectors have been used on single seismometer outputs. We are just beginning to study their behavior when used on MCF or beamformer outputs. Eight such detectors are programmed to operate on signals from the four F-ring and the four E-ring subarrays. The detector outputs are continuously examined, and whenever four or more of the eight detectors operate within a 20-second interval, the decision system indicates that a teleseism has been received. The times of all detector outputs in the 20-second interval ahead of the teleseism decision indication are saved, as well as the times of any detector outputs from sensors not already reported which occur during the subsequent 20 seconds. Pair-wise differences in times reported by four or more subarrays are compared automatically with stored values for a number of pre-selected epicentral regions. When a sufficiently large number of correspondences are found, an event has been automatically located in

that region. All this information is automatically punched on paper tape at LDC and at present is transmitted to Lincoln Laboratory by teletype each day, in time to serve as an aid in the analysis of the previous day's data.

The use of coincidence direction permits each detection channel to be operated at a high sensitivity, but with a low overall false alarm rate for the majority vote detection system. Of course, sensor calibrations and certain types of telemetry errors are registered, but otherwise the residual false alarm rate is of the order of a few per day, and nearly always due to noise bursts of a non-stationary character. We have less than 300 hours of experience with the specific form of event detector logic described here, hence statistically significant results are not yet available. However, the performance is promising, and we plan to operate the detection and location system in its present form for a long enough time to obtain more conclusive results. A few unusually low-frequency or very emergent events have been missed, but the overall performance is at least as good as that of an experienced operator viewing the same traces.

The relative time determinations of the eight detectors have proved to be surprisingly good. For events which are slightly larger than the detection threshold, these times are often within 0.2 seconds of manual time determinations. This is sufficient accuracy to permit a useful degree of event sorting by source position.

Accurate source location, on-line or off-line, depends critically on the knowledge of accurate station corrections. If these corrections are known for each source region well enough so that the r.m.s. fluctuations in station times are of the

order of or below 0.2 seconds, then epicenters can be determined with LASA alone with an accuracy of the order of $\pm 2^{\circ}$. (The 10 db LASA beamwidth is 10° at 7000 km.) This figure has not yet been demonstrated with LASA, but it has been verified at TFO with a network of roughly the same size as LASA. From LASA data collected to date (some 80 events) we now have a fair idea of the station corrections (as functions of source bearing) for the sites in the E and F rings, relative to A0. We had anticipated that the corrections would be smaller for LASA than for TFO, but they are actually of about the same size. For instance, for station F1, we find the corrections (in seconds)

$$+0.6 \text{ at } 145^{\circ}$$

$$-0.1 \text{ at } 245^{\circ}$$

$$-0.2 \text{ at } 310^{\circ}$$

$$+0.2 \text{ at } 000^{\circ}$$

Each number is the mean of all teleseisms occurring within $\pm 10^{\circ}$ of the indicated bearing. We find that the use of these corrections, even in their present rough form, significantly reduces the r.m.s. residual in epicenter determinations based on E-ring and F-ring times. As soon as we have enough data to permit a meaningful study, we plan to find out if there is also a dependence of station corrections on distance and depth.

III. POST-DETECTION PROCESSING

Once a LASA tape recording of a seismic event is available, one may subject it to a variety of processing operations in order to bring out signal features more clearly. Under foreseeable operational conditions the number of events that are to be subjected to modest post-detection processing may be as small as ten per day; those events for which really exhaustive processing is indicated may be one per week. Thus the complexity and expense of signal processing is not as crucial with post-detection processing as it is for predetection processing. On the other hand, the study of seismic sources requires that the processing, while reducing noise and reverberation, must not at the same time impose irreversible distortions on the signal. In the predetection processing described in Section I, the constraints on the problem were exactly the opposite: heavy distortion was allowed (for example, by narrow prefiltering of input traces) but a premium was placed on processing simplicity.

We have investigated the performance of a family of non-distorting signal processing schemes. The difference between these schemes and those described in Section I is that no prefiltering of the traces was employed. In addition, the studies were pushed to the point of using all 525 traces in complex forms of processing, an option that is not really available on predetection without reasonable on-site equipment complexity. The unfiltered results, which are at present much more extensive than the prefiltered results of Section I are summarized in Figs. 4, 5, and 6. As before, the three figures present as the ordinate the gain in SNR of the output trace relative to an average input trace. The abscissas of the three figures are the three fundamental

parameters of any array, namely the number of sensors N, the time aperture T (FS impulse response duration), and the spatial aperture L. N determines the intensity of the main lobe of the array directivity pattern, L the narrowness of resolution in wave number, and T the narrowness of resolution in frequency.

SNR losses outside the fitting interval were observed to be of about the same order for processing of unfiltered traces as those described in Section I for processing of 0.5 to 2.0 cps prefiltered traces. The data in Figure 4 gives SNR gains 30 seconds outside the fitting interval. It is seen that 33 db is typically available under this condition, provided the 25 sensor outputs in each subarray are combined by FS and then the 21 traces thus obtained are likewise combined by FS. However, this procedure, which is the most elaborate we have tried, requires 20 hours of 7094 computer time per event using current programs; less elaborate and thus less effective procedures use correspondingly less time, as indicated by the left-hand small numerals beside each point in the figure. A number of efforts are underway to devise more economical ways of doing such processing. Some of these are described in our current Semiannual Report. At present, approximately half the computing time for FS and WDS is used for computation of the correlations of the noise sample. If this step can be shortened (for example by starting from previously computed noise data), a substantial time saving can be achieved.

Systematic studies of the desired length of the fitting interval have been made for unfiltered traces. This is reported in some detail in our current Semiannual Report.

The conclusion is that a three-minute interval is a reasonable compromise between the need to reach statistical equilibrium and the desire to minimize computer time.

Figure 5 shows SNR gain in the fitting interval as a function of the number of filter points in each filter function. Along the lower curve the filters are "physically realizable," a term borrowed from electrical filter theory. That is, the sum of their impulse responses is zero for all values of delay except the first one at which the sum is unity, so that the filter operates on the basis of only past samples of the noise. Along the top curve the filters are symmetrical, i.e., the sum of the impulse responses is zero except at the center sample point at which they sum to unity, so that the symmetric filter operates on the basis of the future as well as the past values of the noise. Such filters are permissible with recorded data, but do not exist for live data, since a response before excitation is implied. They are thus said to be "physically unrealizable." The other curves represent unrealizable filters whose buildup point is intermediate to that of the realizable filter and the symmetric filter. The results clearly indicate the superiority of the symmetric filter in yielding a high signal-to-noise ratio gain over the asymmetric filters. A figure of 21 filter points was used in all the processing of the various events reported here. One hazard in using an unrealizable filter is the possibility of an unwanted precursor in the output trace, but we have found that this problem can be managed. This is discussed in Section IV in connection with observations of first motion.

Figure 6 summarizes the results of two separate experiments designed to determine the effect of aperture on SNR gain. In the first experiment, indicated by the

shaded bars, the FS outputs from four subarrays arranged in rings of various diameters L were combined by DS, WDS, and FS. (The gains in the fitting interval for combining 21 subarray FS traces on this particular event were 35 db for DS, 36 for WDS and 38 for FS.) For all three forms of combining groups of four subarrays, the SNR gains are seen to be relatively independent of L. In the second experiment, indicated by the unshaded bars, 25 sensors forming arrays of various aperture were drawn from the 525 available and processed by DS, WDS, and FS.

It is seen that DS and WDS did not perform competitively until the aperture reached around 20 km or more. FS performance began to depreciate for apertures larger than one subarray diameter. If these results are typical, it would appear that FS is very useful within one subarray of diameter between 7 and 20 km; beyond that aperture, simpler schemes will suffice. For large numbers of sensors (say 100) arrays will yield approximately the same SNR gain independent of aperture beyond 20 km. Proper interpretation of this data depends on knowing the physical nature of the high-velocity, short-period noise (mantle P-wave noise) which can only be completely clarified by experiments in progress to produce high-resolution f-$\vec{k}$ maps of noise. It should be emphasized that although the data of Fig. 6 indicates that large apertures may not be required for purposes of achieving SNR gains, they are necessary for event screening by location (see Section II) and for reduction of coda complexity (see Section IV).

A few cautions are in order about the significance of the SNR gains obtained from unfiltered traces, as given in Fig. 4. The data does not represent SNR gain at the frequency of the P-wave signal. We have done experiments on this question using very

narrow prefiltering (several tenths of a cps) set exactly at the P-wave frequency and have observed gains somewhat higher than those in Fig. 2; but it was then found that in order to have a fixed event detector filter characteristic that would not miss some events the wider 0.5-2.0 passband was needed. With the available degrees of freedom in the processor deployed over wider bandwidth the SNR gains decreased slightly to the values given in Fig. 2. With no prefiltering of the traces at all, the large gains of Fig. 4 are observed, partly because the processing is so effective against trapped mode noise which is at a lower frequency than P. If there is a feature of the seismogram that has the same spectrum as the noise on a single sensor, then the db gains in Fig. 4 can be interpreted directly as an equivalent increase in magnitude units of the visibility of that feature. If not, the correspondence cannot be made. For example the 1 cps P-oscillation is clearly not 20 db more visible after FS processing of a single subarray. What is true is that if the seismogram is to be reproduced without any distortion due to frequency selective filtering, then 20 db of gain against the noise that is present over the entire LASA seismometer response band is typically achieved for FS on a single subarray.

The ability of the LASA to reject unwanted teleseismic phases in favor of desired ones is important for several purposes; for example, nuclear test surveillance during a strong earthquake. The three portions of Fig. 7 show the results of using a part of the LASA in such an experiment. A roughly linear end-fire array of 32 km length was formed from 17 selected sensors and used on data from the Longshot explosion. In Fig. 7A and B, simple DS processing was done using a number of values of assumed

horizontal phase velocity. The traces with the theoretically correct velocity for P and PcP are appropriately labelled, and it is seen that 14 db suppression of one phase in favor of the other occurs. In Fig. 7C it is seen that when the more complex FS type of processing was applied, with the fitting interval extending from one minute before P until one minute after the P-initiation, and with the PcP velocity used as the desired signal velocity, a 32 db suppression was obtained. The processing acted to reject energy with the spatial properties of P as though it were noise, i.e., it pointed a strong null in that direction and favored the PcP value of velocity.

One final result deserves mention. We know that these are observable r.m.s. differences of up to ± 15 percent in signal amplitude and ± 12 degrees in phase across a subarray. However, these do not lead to any appreciable loss in the FS signal output. The spurious precursors introduced by use of unrealizable filters in the presence of signal amplitude inequalities seem not to be a severe problem (see Section IV). These results lead to the conclusion that the FS processing is not too sensitive to the assumption that the signal be identical across the subarray.

We can summarize the off-line processing capability of LASA as follows:

(1) In using non-distorting array processing, gains in SNR of up to 33 db can be attained on the average event if the fitting interval ends within less than 30 seconds before the event. Currently many hours of computing time per event are required. For lesser computing times figures giving the lesser numbers of db gains are available.

(2) If the noise statistics are one week old, this maximum figure becomes 27 db.

(3) It appears that for fixed N, the SNR gains are somewhat insensitive to aperture in the range 20 to 200 km, at least for short-period P-waves.

(4) Rejections of unwanted teleseismic phases of over 30 db are easily obtainable with less than 25 sensors. Attempts have not been made to push this further by using larger N.

IV. SEISMIC SOURCE IDENTIFICATION

The ability to make 525-channel LASA recordings, which has existed at the Billings, Montana, LASA Data Center since September, has provided us with a library of some 96 events so far, of which five are nuclear explosions. We are thus in a position to begin investigating systematically the blast-earthquake discrimination problem using LASA data. Some of the proposed criteria for discrimination (or more accurately for classifying events as either earthquakes or unidentified events) are direction of first motion, depth of focus, complexity, energy ratios (e.g. P/S, LR/LQ), aftershock patterns, and spectral shape. To be fully effective, the first three of these all require observations at a number of globally separated stations, and yet it should be possible for us to make a partial appriasal of the effectiveness of a hypothetical network of LASAs by examining data derived from the experimental one in Montana. Such an effort has just been started and we have several fragmentary results to report.

We can give only two results on first motion. First, on one known explosion a rarefactional first motion was apparent from examination of raw traces, whereas after maximum-likelihood processing, compressional first motion was seen on most of the subarray outputs. Specifically, upon processing the fraction of traces with rarefactional first motion went from 40% to 20%, those with compressional first motion from 10% to 70%, and unclear first motion from 50% to 10%.

Secondly, it is known that when unrealizable filters are used, misleading half-cycle precursors can sometimes be introduced in the maximum-likelihood output trace because of violation of the assumed condition of signal identity across the subarray, for

example due to large differences in seismometer gains and/or time misalignments. We are finding such precursors only very rarely; in 37 subarray outputs from known blasts, only 11 had an observable precursor. The largest one seen was 20 db down from the largest half cycle. In practice, as long as determination of first motion is based on outputs from more than one subarray, this should constitute no problem. One can always eliminate precursors completely by using completely realizable filters, but at a loss in SNR gain.

To compare the complexity of signals before and after array processing both individual seismometer and processed traces from two events are shown in Figs. 8A and B. The first of each pair of traces is the unsmoothed trace while the second is a plot obtained by rectification of the trace followed by smoothing with a 2 second time constant. Two individual seismometer outputs, two subarray maximum-likelihood outputs, and the outputs of the maximum-likelihood processing of the subarray max-likelihood traces have been plotted in each figure; in Fig. 8A for the 11/11/65 Rat Island earthquake, and in Fig. 8B for a Kazakhstan event.

Both the observation of depth phases (for example, pP following P) and the use of the complexity criterion require that reverberation introduced into the coda of a given primary phase be reduced as much as possible. The large aperture of LASA seems to be of considerable effect in this respect, although Fig. 8 indicates that this is somewhat more apparent on the output traces themselves than on the envelope plots derived from them, possibly because the 2 second smoothing time is too long.

The S-phase arrival is not often recorded on short-period vertical instruments. However, it was felt that an effort should be made to find the S-phase on both earthquake and explosion records. Data from Longshot, from an earthquake on November 11, 1965, from nearby Rat Island and from a Kazakhstan event were all processed by maximum-likelihood processing aimed at S for the time period covering the S arrival. The Longshot data was taken from the 17 seismometer 32 km array already described while the Rat Island and Kazakhstan events were processed using the 25 seismometers of Subarray B1. For these events the noise power was reduced by approximately 14, 23, and 14 db, respectively; however, no S waves were visible in the processed traces.

The search for phases in the intermediate period range (2-10 secs) is continuing. Because of the high level of microseismic noise it has been almost impossible to study the phases of weak teleseisms in this band. The SNR gain achievable from spatial filtering of LASA data makes this an attractive area for further active study.

3-64-4582

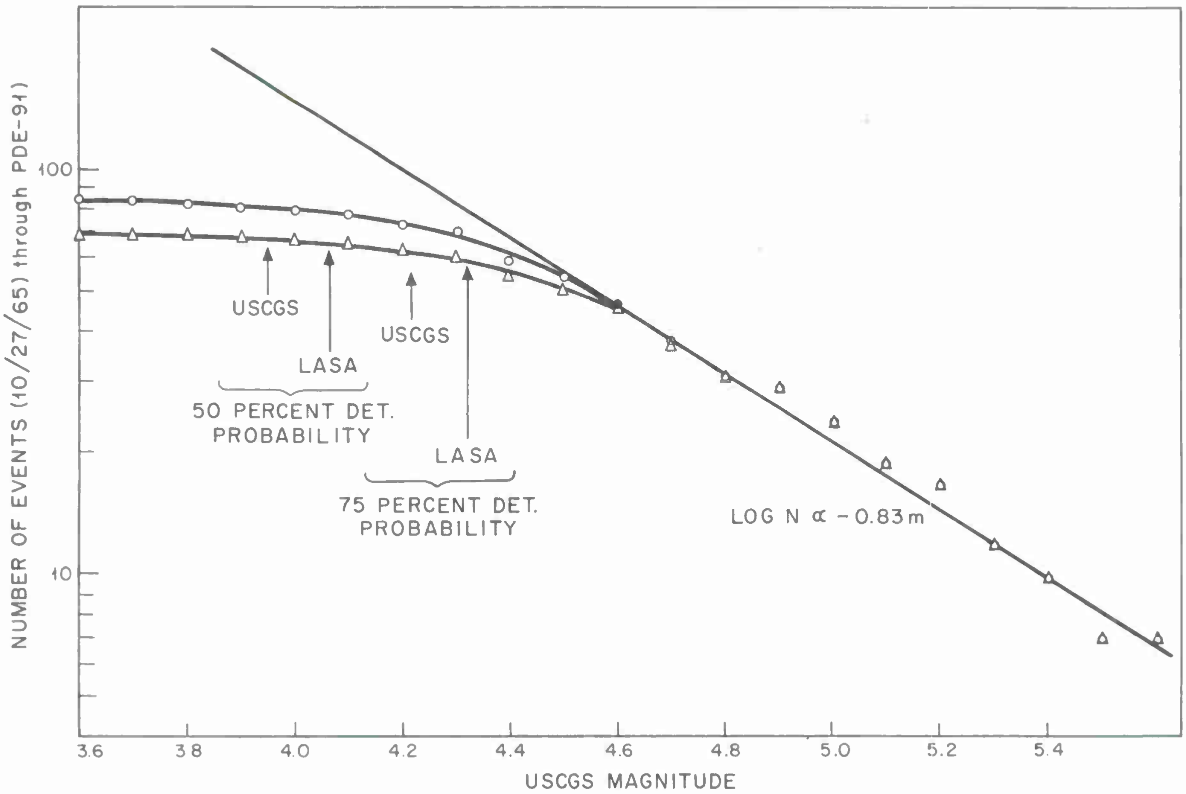


Figure 1 Number of detected events larger than a given magnitude vs that magnitude. Circles are for U.S.C.&G.S. and triangles are for LASA. Assuming a linear law of log N vs m, the threshold for 50% detection probability on raw LASA traces is 4.07, and for 75% detection probability it is 4.32.

3-64-4583

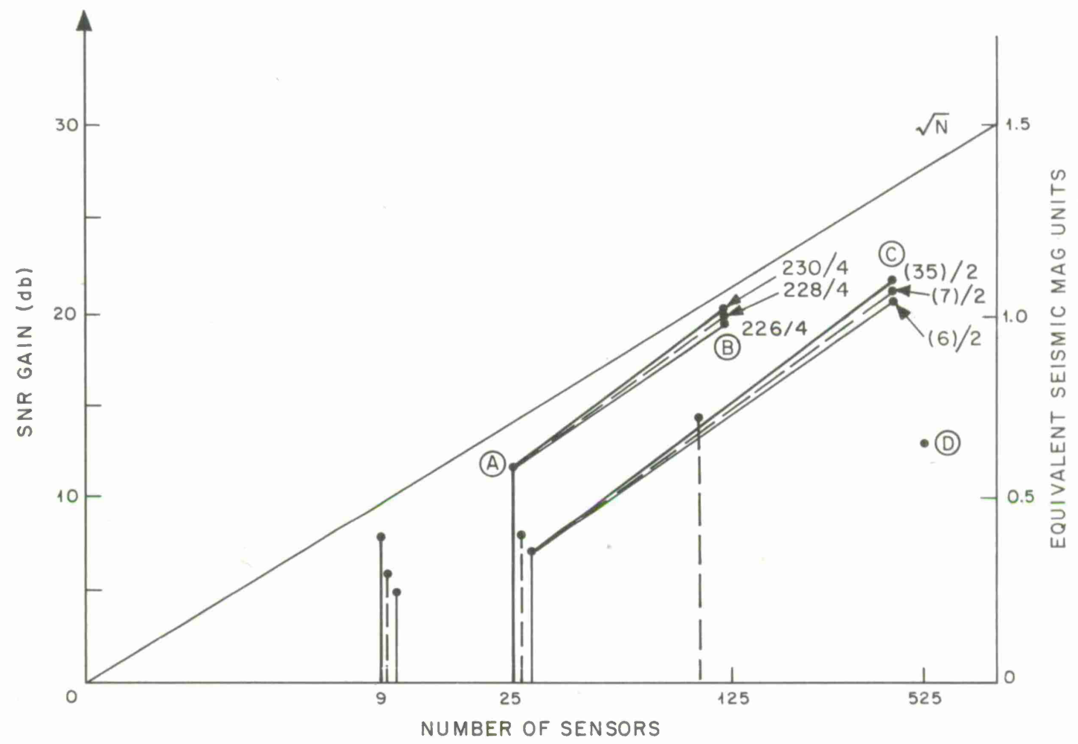


Figure 2 SNR gain vs number of sensors processed when the traces are prefiltered with a 0.5 – 2.0 cps passband. For FS and WDS processing the SNR was measured 0.5 minute outside the fitting interval.

3-64-3190(5)

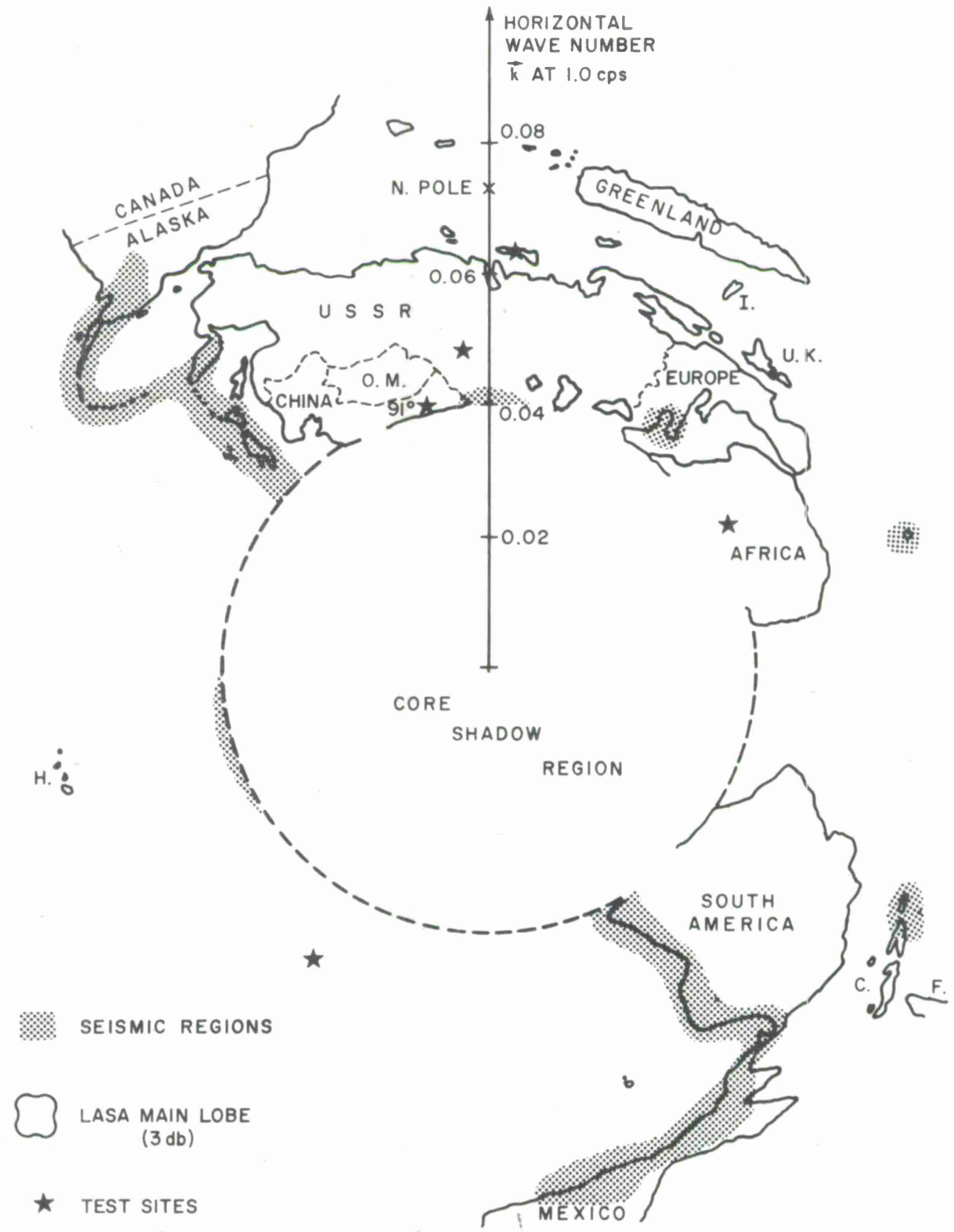


Figure 3 Map of the P-phase sources in wave number at 1.0 cps. The shape of the main lobe of the LASA beam pattern anywhere on this diagram is shown at the lower left.

3-DO-3069

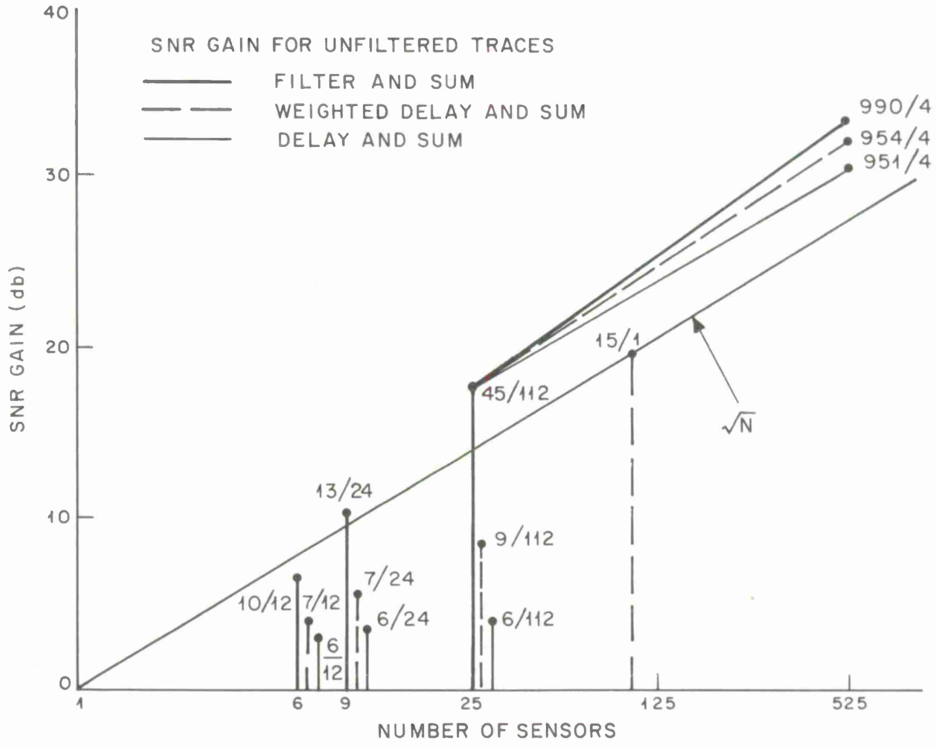


Figure 4 SNR gain vs number of sensors processed when the traces are not prefiltered. For FS and WDS processing the SNR was measured 0.5 minute outside the fitting interval.

3-DO-3068(1)

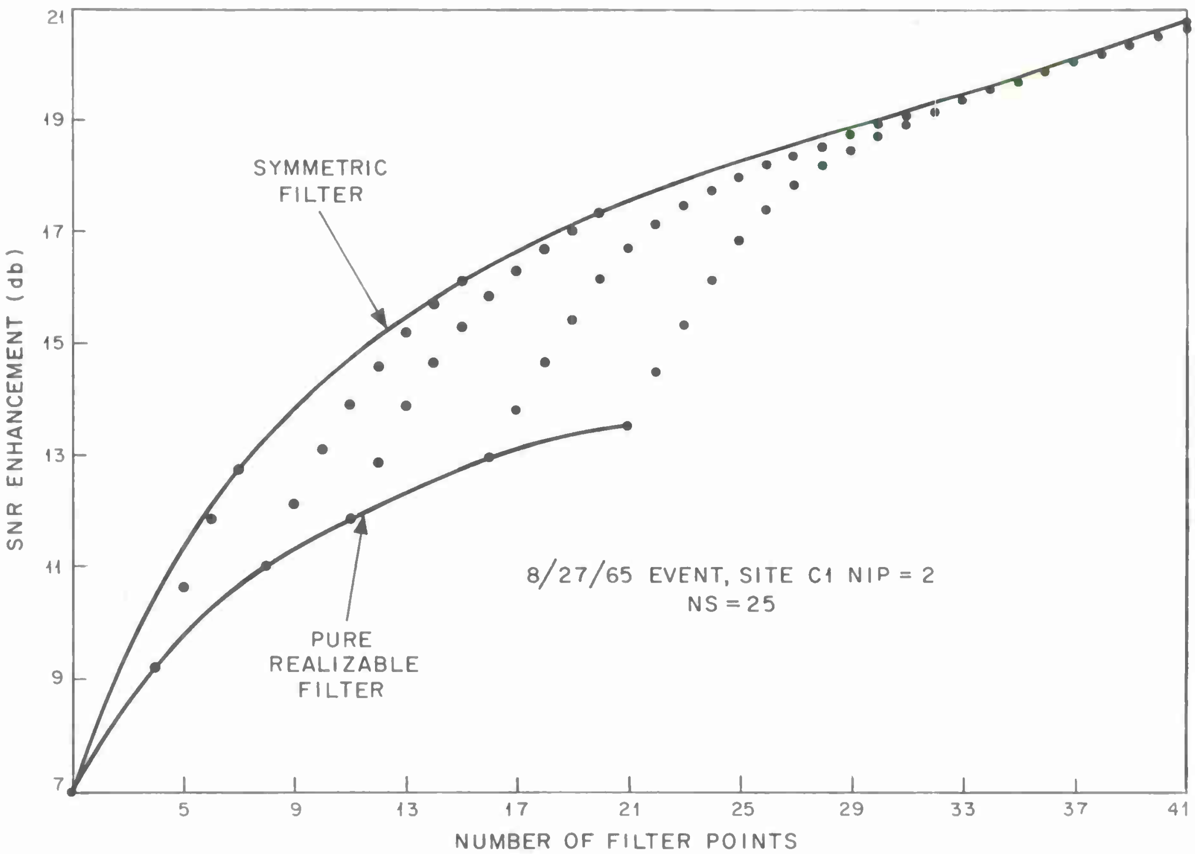


Figure 5 SNR gain vs length of the filter functions used in FS processing. The filter points are 0.1 second apart. (WDS processing is the special case for which the number of filter points is unity.)

3-64-4584

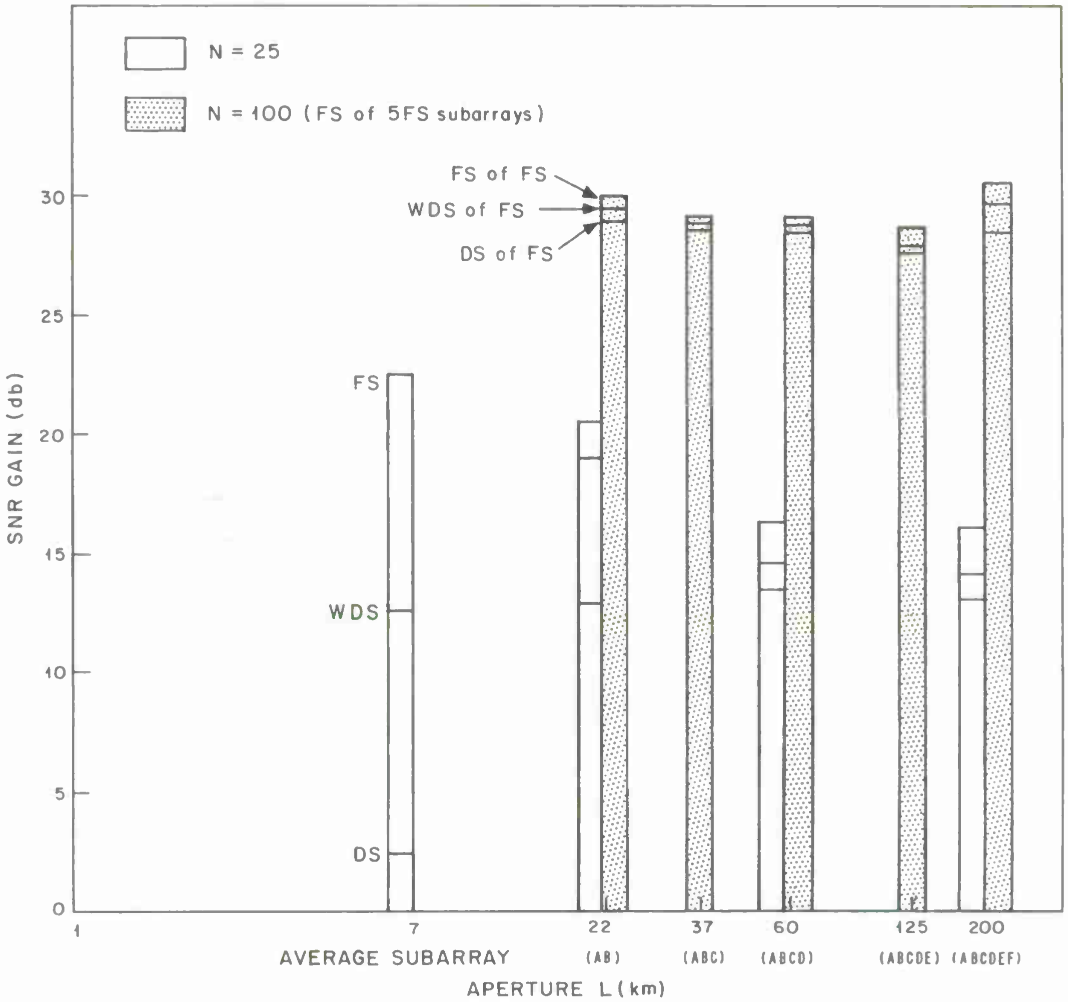
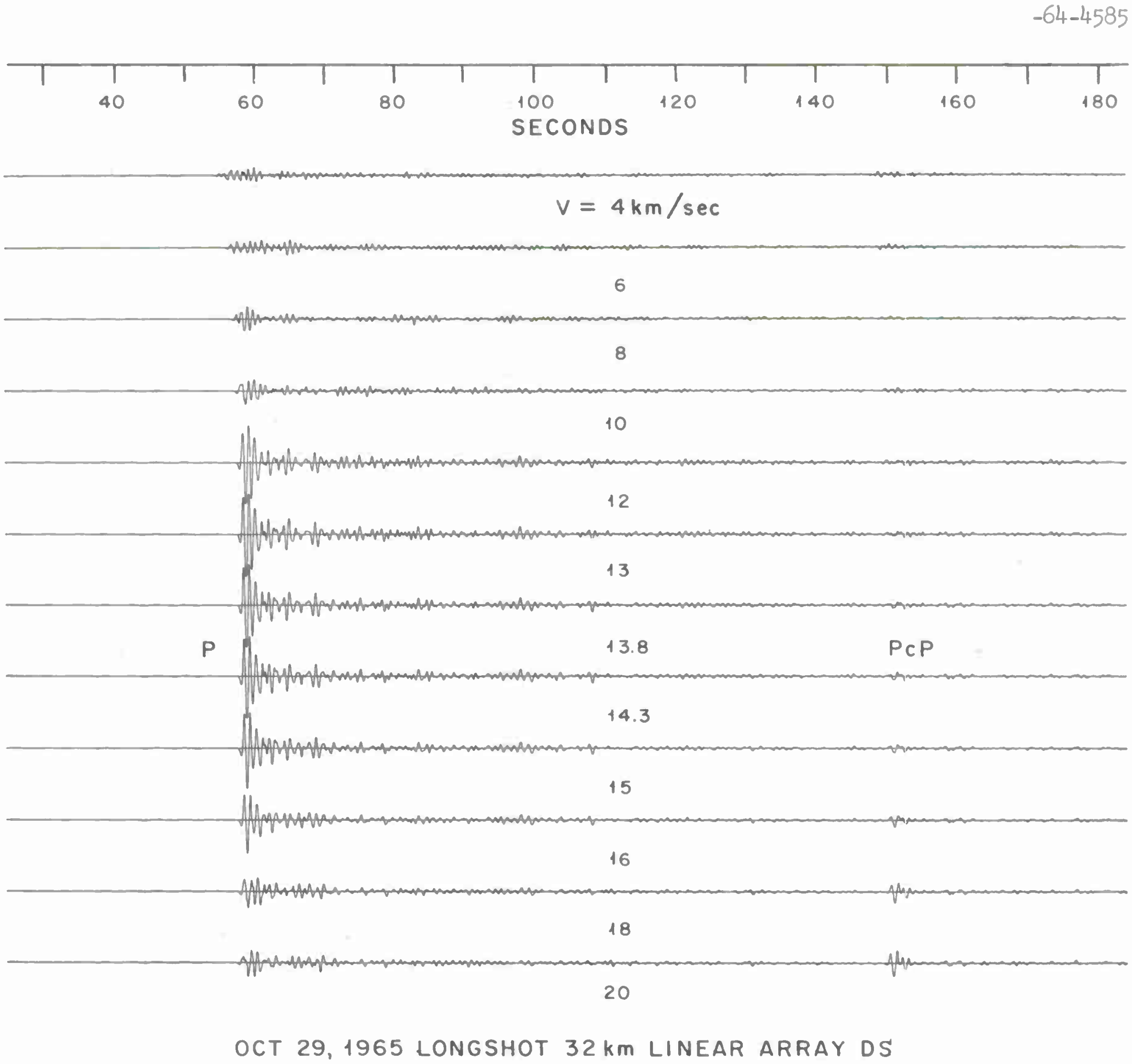
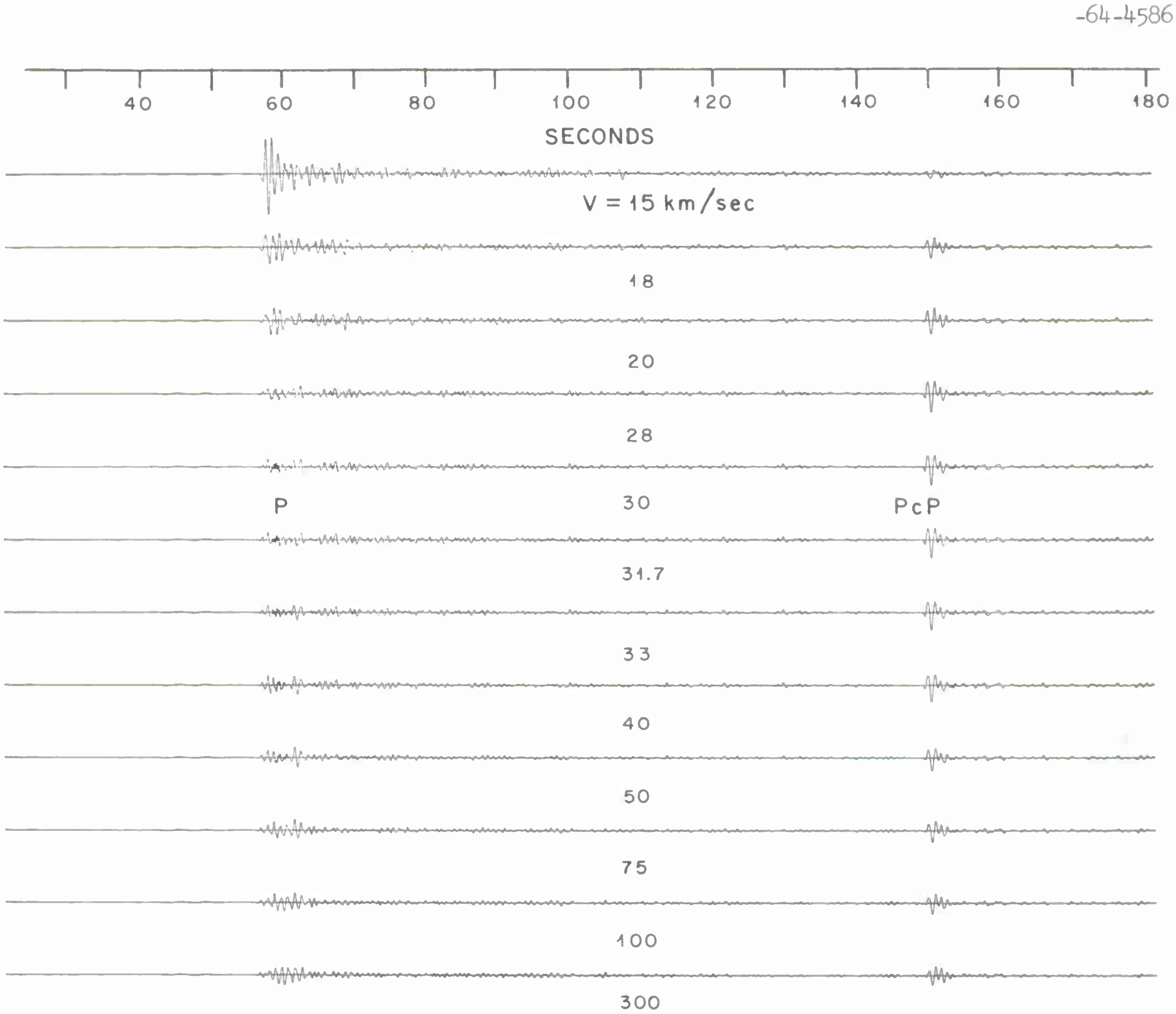


Figure 6 SNR gain vs aperture (Rat Island event of Nov. 11, 1965, CGS mag = 5.0). For FS and WDS, the SNR gain was measured in the fitting interval which lasted 10 minutes for N = 25 and 3 minutes for N = 100.



Illustrating the use of array directivity to suppress an unwanted signal in favor of a desired one.

Figure 7A Use of delay and sum (DS) processing to suppress PcP in favor of P (at 13.8 km/sec).

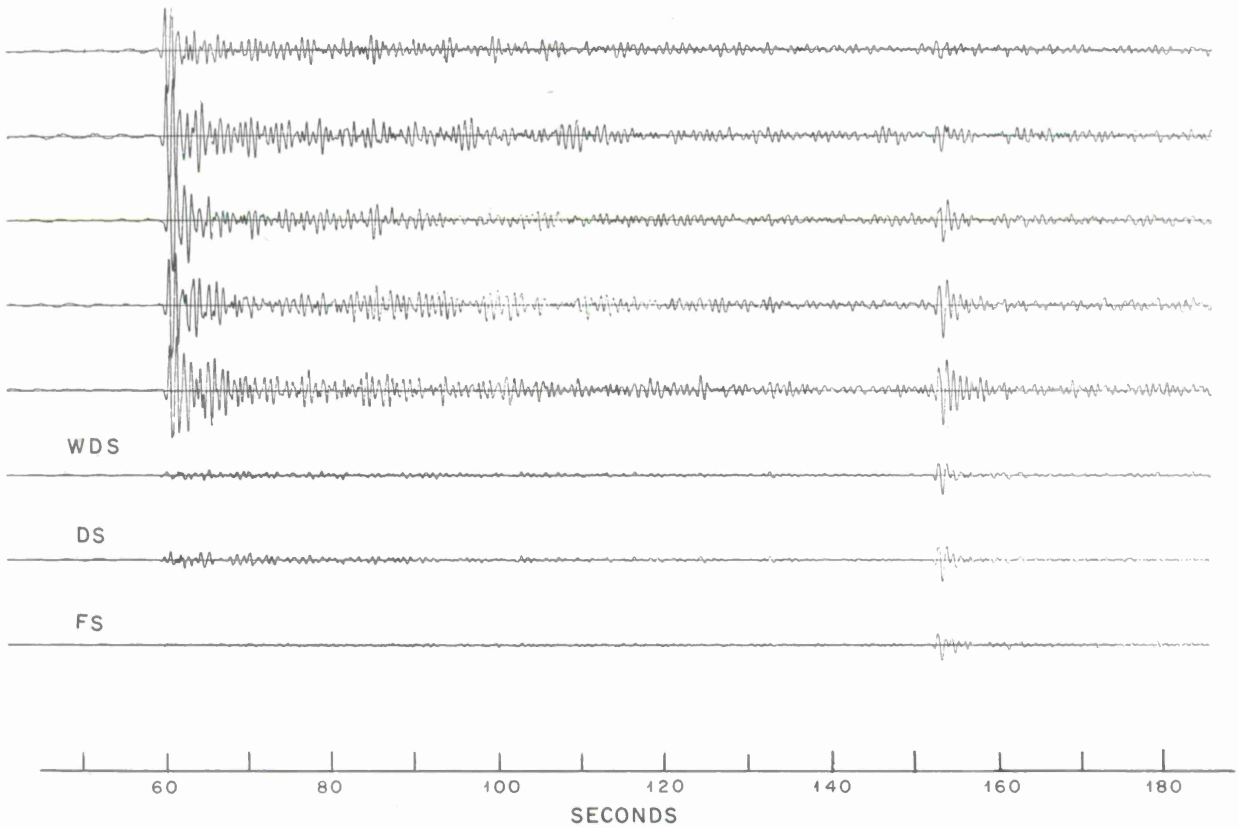


OCT. 29, 1965 LONGSHOT 32km LINEAR ARRAYS DS

Illustrating the use of array directivity to suppress an unwanted signal in favor of a desired one.

Figure 7B Use of delay and sum (DS) processing to suppress P in favor of PcP (at 31.7 km/sec).

-64-4587



OCT 29, 1965 LONGSHOT 32 km LINEAR ARRAY DS, WDS, FS

Illustrating the use of array directivity to suppress an unwanted signal in favor of a desired one.

Figure 7C Use of filter and sum (FS) processing to suppress P in favor of PcP on the same event (Longshot). The largest oscillation in the P-coda of the FS output is 32 db smaller than the single-trace P amplitude.

-60-4485

INDIVIDUAL SEISMOMETER

INDIVIDUAL SEISMOMETER

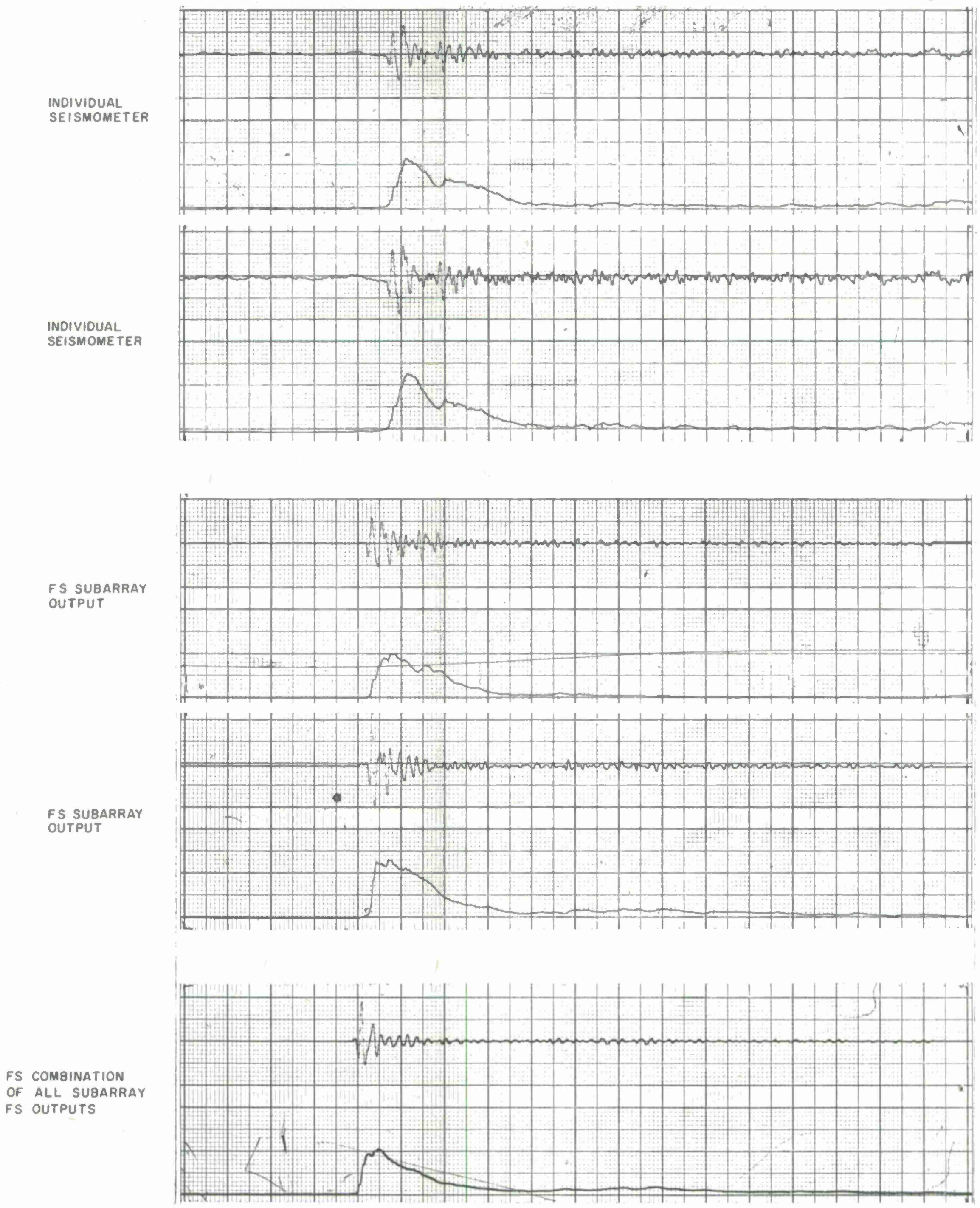
FS SUBARRAY OUTPUT

FS SUBARRAY OUTPUT

FS COMBINATION OF ALL SUBARRAY FS OUTPUTS

Effect of LASA signal processing on the P-phase of one earthquake and one presumed explosion.

Figure 8A Rat Island event of November 11, 1965.



Effect of LASA signal processing on the P-phase of one earthquake and one presumed explosion.

Figure 8B Kazakhstan event.

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13. ABSTRACT

This report presents an interim appraisal of capabilities of a single Large Aperture Seismic Array system to perform the following functions: (1) preprocess arriving seismic signals to increase their detectability, (2) use such preprocessed signals to perform on-line automatic detection and location, (3) process recordings of LASA data off-line, and (4) use the results of the off-line processing for studies of seismic source type.

14. KEY WORDS

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